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Baluns For Microwave Applications Part 1

In applications involving mixers and push-pull rf power amplifiers, baluns are used for the transition from the symmetrical to the asymmetrical section. Whilst for short-wave applications a transformer can be used, many different techniques are used for UHF applications.

1. Introduction

In rf technology, baluns (balanced to unbalanced) play an important role. In antennas, we need to guarantee a transition from the coaxial line to the symmetrical two-wire system with as little reflection as possible. The same is needed in the rf electronics itself, i.e. in the designing of mixers and, in particular, in push-pull power amplifiers. A good overall view of various types of balun (even if it is not complete) can be found, among other things, in [1-3].

A balun has to have the following characteristics:

- As precise a 180° phase shift as possible must be maintained between the two terminals of the symmetrical port.
- In power amplifiers, the impedance presented to the symmetrical port must be equal. If this is not the case, then there will be a decrease in the efficiency.
- The symmetrical port must be well isolated from earth. This is especially important for power amplifiers, since parasitic oscillations can occur.
- The insertion loss should be kept as low as possible.

When power amplifiers are used in class C, not only is an optimal loaded impedance needed at the operating frequency, but a very low-impedance load is needed at the second harmonic, with an open circuit at the third harmonic, in order to obtain optimal amplifier efficiency [1].

The basic idea behind the construction of a balun can easily be outlined. Two signals 180° out of phase (symmetrical port) are "synchronised" in their phases and their outputs are added. Many designs involving $\lambda/4$ phasing lines (90°) and $\lambda/2$ phasing lines (180°) have crystallised out of this basic idea.

Over time, a large number of designs have been collected. This article, though, will concentrate on designs that can be realised using no more than double-sided printed circuit boards, and that are used for applications in push-pull power amplifiers. Naturally this implies the use of microstrips and discrete components

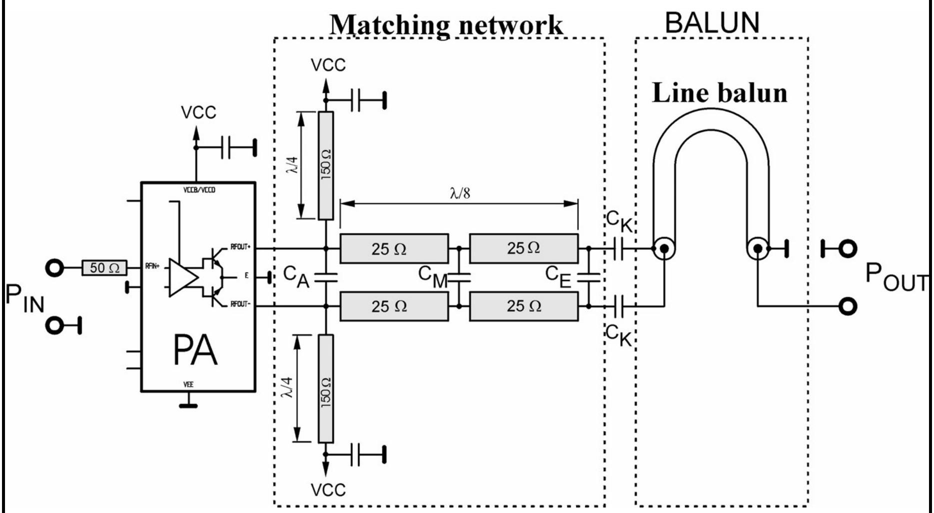

Fig. 1: Line balun with matching network.

such as coils and capacitors. A line based solution will be discussed first followed by the LC balun and its further developments.

2.

The line balun with matching network

Fig. 1 shows the optimal design for a power amplifier balun in the range from approximately 400MHz to 1.5GHz.

The actual balun is in this case a λ/4 long line section with a series connected matching circuit. The line balun described in [1, 3] (called a bazooka balun in [3]), we are normally dealing with a semi-rigid line with Z_w = 50Ω. The length is precisely λ/4. As a rule we can still not achieve optimal matching with the line balun alone, an additional matching network is connected to it in series. This consists of a microstrip, with an impedance, Z_w, of 50Ω and trimming capacitors.

Since power amplifiers are usually matched with a low load impedance, this results in a Zw which must be lower than 50Ω (cf. λ/4 transformer equation). The precise impedance can thus be selected to have another value, depending on the desired input impedance of the balun. With C_M and C_E, the real and imaginary components of Z_0 can be set. The capacitors, C_K, act as DC block capacitors. The DC feed comes through two λ/4 transformers. This gives a short-circuit, at the second harmonic, at the two collectors of the rf transistors, because the λ/4 transformer transforms a short-circuit into a short-circuit again at double the fundamental frequency, $2f_0$.

An open circuit is achieved on the collectors of the rf transistors by means of a resonant circuit with C_A at third harmonic, $3f_0$. This circuitry is required to achieve a high efficiency in non-linear operation. Fig. 2 shows a 900MHz power amplifier with an integrated circuit. This IC contains a push-pull power amplifier that is set to a 50Ω output using the

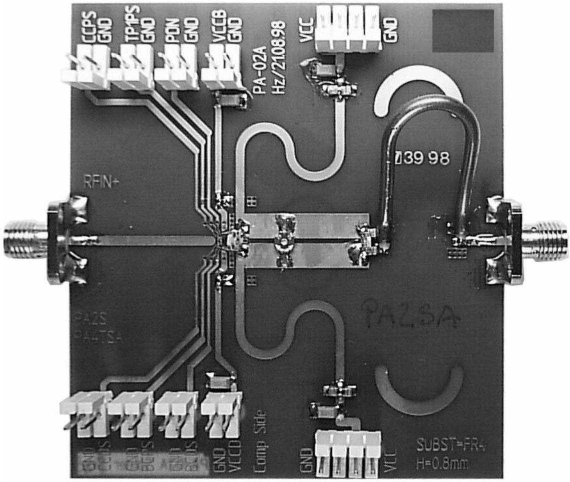

Fig. 2: A 900-MHz GSM power amplifier module with line balun.

circuit described above.

This design has two disadvantages:-

- The electrical length of the λ/4 line section must be guaranteed within narrow tolerances.
- The design requires manual calibration.

The length of this λ/4 line also represents the limit for the application at low frequencies, since this becomes longer as the frequency decreases.

If the frequency exceeds 1.5GHz, it is apparent that trimming capacitors are practical up to a maximum of 1.5GHz, since better microwave trimming capacitors have their resonant frequency at 1 to 2GHz. Thus this design is unusable for frequencies exceeding approximately 1.5GHz. On the other hand, it offers an optimal load impedance, among other things, for the amplifier in that, even for the non-linear application case (class C) even the harmonic load can also be matched. Thus this design can be used to achieve very high efficiencies, which is not possible with fundamental frequency matching alone.

3.

The LC Balun

The LC balun [2, 5] is actually a bridge circuit (Fig. 3) and is also referred to in English speaking countries as a “lattice-type” balun. It made its first appearance in a patent document from 1934 (C.Lorenz AG Berlin, Tempelhof)[5]. It consists of two capacitors and two inductances, which create a phase displacement of ±90° for each connection of the symmetrical input.

One very good characteristic of the balun is the ability to match any symmetrical input impedance and any asymmetrical real output impedance. Moreover, it is outstandingly suitable for integration, and is therefore also used for smaller power amplifiers (Fig. 4). We should also look at the power supply of rf

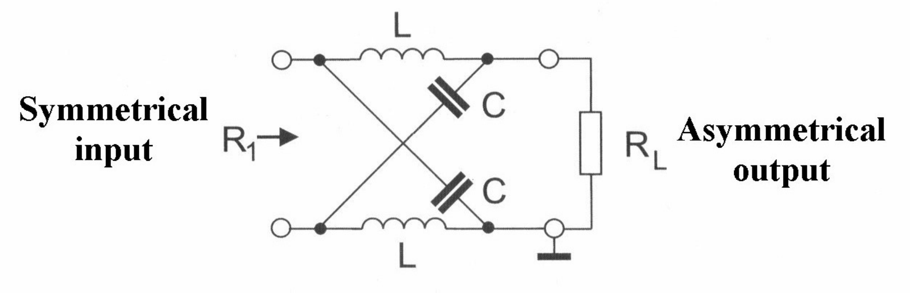

Fig. 3: The LC balun bridge in classical representation.

transistors. If the whole assembly is mounted on a double-sided printed circuit board, then the rf shunt can be replaced by a radial stub [6-8] and the choke by a λ/4 transformer with an impedance as high as possible.

For calculation:

1. First all impedances and the operating frequency are determined. Using the formula to calculate the circuit frequency:

$$\omega = 2\pi f$$

Subsequently, the characteristic impedance of the bridge circuit can be determined using the expression:

$$Z_c = \sqrt{R_1 \cdot R_L}$$

where R_1 is the symmetrical input resistance from Fig. 4 and R_L.

2. Now the component part values are determined. For the typical case in which real impedances are used:

$$L = L_1 = L_2$$

and:

$$C = C_1 = C_2$$

For the inductances, L, we obtain the expression

$$L = \frac{Z_C}{\omega}$$

and for the capacitances

$$C = \frac{1}{\omega Z_C}$$

The important thing about this calculation is that we are assuming that the components are ideal and, more importantly, that the connection lines are infinitely short. If we now construct such a bridge for high frequencies (from 500MHz), we should also take the connection lines into account. With a simulation tool such as Ansoft Serenade [S1] or Eagleware Genesys [S3], this is done by inserting the appropriate microstripes (for tracks) and/or inserting computed inductances (1mm wire 1nH).

We should also take care that the load impedance actually corresponds to reality (is the connection line, for example, actually 50Ω? what happens if a DC block is used?) otherwise the above equations will not apply.

When selecting component parts, we should take care that we are operating below their resonance frequencies which becomes more and more difficult as the frequency increases. So it is recommended to use the S-parameter files from the component part manufacturer. We soon understand here that the lumped component parts used put an upper frequency limit on the design.

Using microstrips as a replacement for

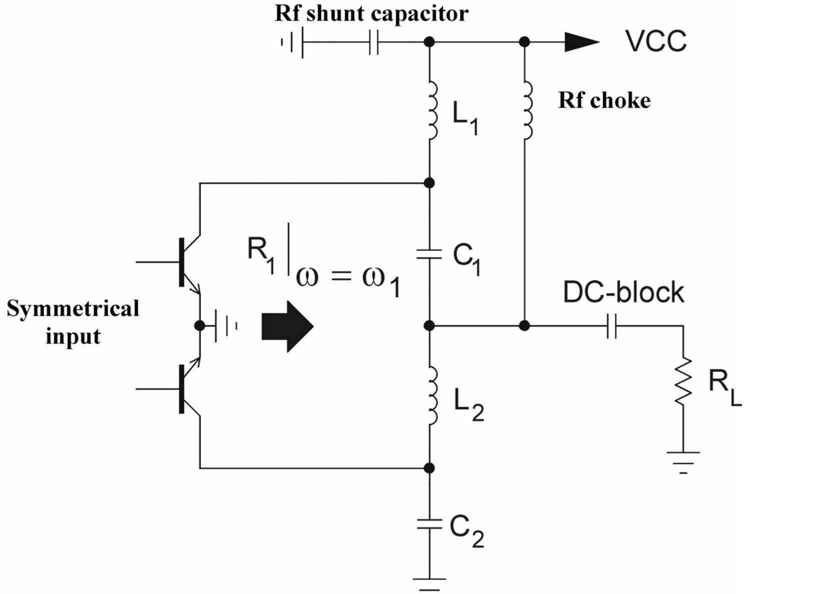

Fig. 4: The LC-balun for a push-pull power amplifier.

the lumped component parts can be a solution:-

An inductance can be realised by selecting an appropriate ratio between the line impedance and the length. Likewise, a capacitance can be realised by using an open circuit microstrip. A good rf short-circuit (rf shunt) can be created using a radial stub [6-8].

4.

The Microstrip Based LC Balun [9]

With the knowledge that we can replace lumped component parts by microstrips, we can design a balun that makes use of these features. Fig. 5 shows such a balun:-

In comparison with an LC-balun using discrete component parts, this type of design has a number of advantages:

Saving on expensive microwave component parts

Greater freedom to design with a simulator (every miscrostrip is defined in terms of length and width). We can also obtain a low load impedance for the second harmonic and an open circuit for the third harmonic.

A direct power supply feed for the power transistors of a push-pull amplifier is made possible through the line structure.

The radial stub fulfils two tasks here:-

- Rf shunt for the power supply
- Defined shunt for the inductance L1

A method for the calculations of this balun is available when using the example of Ansoft Serenade. The above balun has been calculated and simulated for an operating frequency of 2.45GHz and symmetrical input impedance of 28Ω. The substrate used was Rogers RO4003, with a substrate thickness of 510µm and $\varepsilon_r = 3.38$.

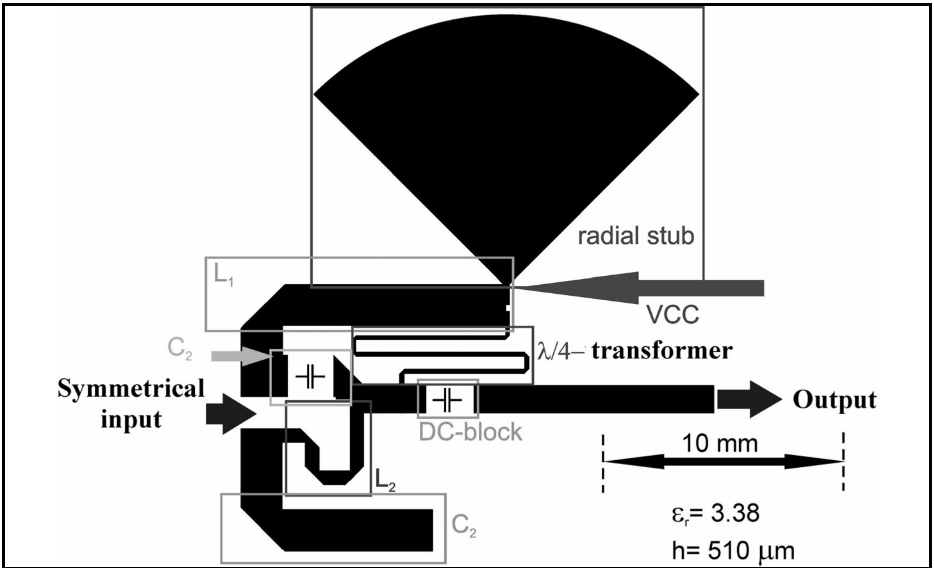

Fig. 5: Microstrip LC balun for the 2.45GHz ISM band with a differential input impedance of 28Ω . (Substrate: Rogers RO4003 with ε_r = 3.38 and a thickness of 0.510mm.).

To determine the track widths it is best to use the “Transmission Lines” tool from Serenade, or something similar such as, for example, Appcad [S2]. We obtain a width of approximately 1.15mm. for a 50Ω line.

(To be continued)

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Software on the internet

[S1] Ansoft Serenade 8.5: http://www.ansoft.com, A restricted student version is available

[S2] Appcad 2.0: http://www.agilent.com/, This is a freely available tool for all possible calculations involving electrical engineering and metrology

[S3] Eagleware Genesys: http://www.eagleware.com, Not to be confused with the Eagle CAD program from Cadsoft. You can also, from time to time, find a demo version of the Eagleware Genesys Suite on this page

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Baluns for microwave applications - part 2

Continuation

To determine the track widths of a microstrip-based LC balun [9], it is best to use the “Transmission Lines” tool from Serenade, or something similar such as, for example, Appcad [S2]. Here we obtain a width of approximately 1.15mm. for a 50Ω line.

4.1. Dimensioning of an ideal LC balun in accordance with Section 2:

For the load R_L = 50Ω and a differential input impedance of R_1 = 28Ω, we obtain a characteristic impedance of

$$Z_C = \sqrt{R_1 \cdot R_L} = 37.4\Omega$$

Thus with f = 2.45GHz, we can use the formulae (1) to get the values for C = 1.73pF and L = 2.43nH. Fig. 6 shows the Serenade circuit diagram for the first simulation run and Fig. 7 shows the result, which reproduces a differential feeding of the balun with two ideal transformers (S_{33}). To ensure that this differential impedance does not arise due to complete asymmetry of the two connections, the two connections for the differential input must be individually inspected for two-port balance. With a symmetrical resistance of 28Ω, this gives the termination through 2 x 14Ω (port 1 (S_{11}) and port 2 (S_{22})). We can already recognise the phase displacement by 90° of connections 1 and 2 on the Smith chart (Fig. 7) whilst perfect matching is obtained differentially (port 3).

4.2. Substitution of concentrated structural elements:

First the substrate wavelength is determined for the simulation:

$$\lambda_{op} = \frac{1}{f_{op} \cdot \sqrt{\varepsilon_{reff} \cdot \varepsilon_0 \cdot \mu_0}}$$

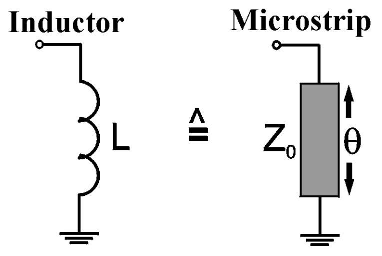
where

f_{op} is the operating frequency and

$\varepsilon_{r,eff}$ the effective permittivity.

An estimation with $\varepsilon_{r,eff} \cong \varepsilon_r$ as start parameter is completely adequate for the following simulation, but the calculated lengths will all depart somewhat from the physical lengths.

Substitution of L1 [1]:



$$\omega_{L1} = Z_0 \cdot \tan\theta \qquad \theta < 90^o \left(90^o \frac{\lambda_{op}}{4} \right)$$

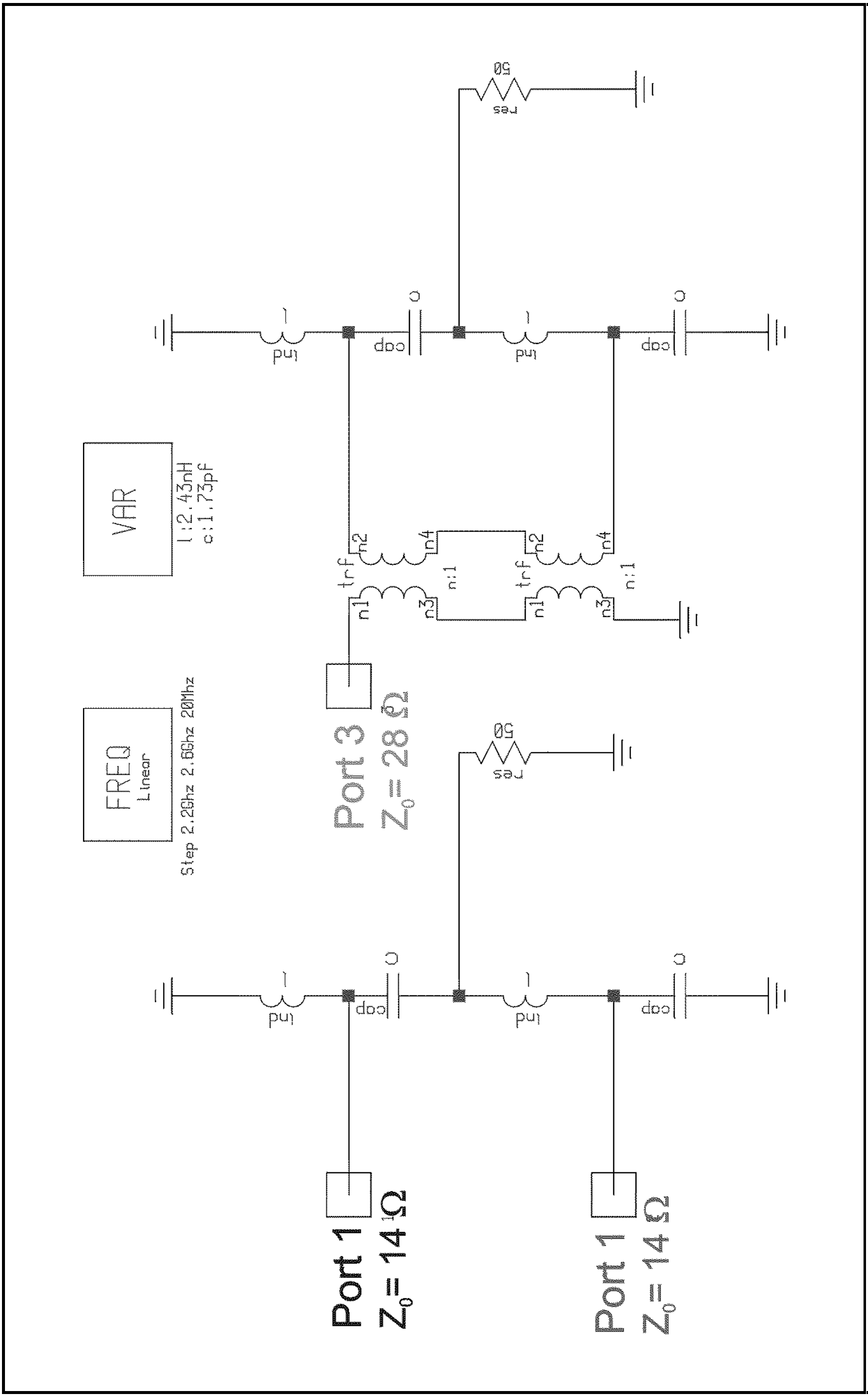


Fig 6 : Circuit diagram from Ansoft for the ideal LC balun.

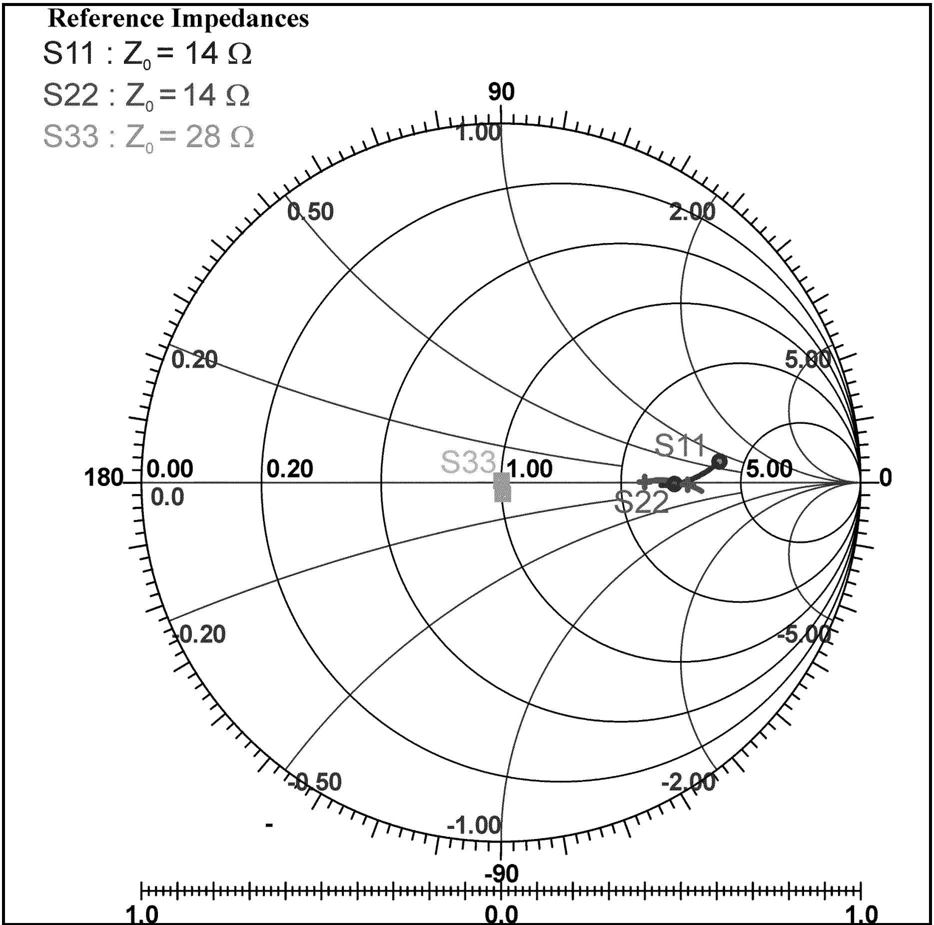


Fig. 7: Impedances of LC balun: S_{11} and S_{22} represent the impedance of a connection to earth in each case. Note the 90° phase displacements of S_{11} and S_{22}.

If we select Z_0 = 38Ω for this, we obtain for

$$\tan\theta = \frac{2\pi \cdot 2.45GHz \cdot 2.43nH}{38\Omega} \approx 1$$

With the relationship tan (45°) = 1, we obtain the length of the microstrip, since correspondingly.

$$\frac{\lambda_{op}}{8} = 45^o$$

The length is calculated using λ_{op} = 67mm at

$$L_1 = \frac{67mm}{8} \approx 8.3mm$$

as the start parameter for the following simulation.

Substitution of C1 [1]:

The substitution of the series capacitance is not possible unless a λ/4 phasing line is used. Since a line of this kind of length would lead to a severe limitation of the

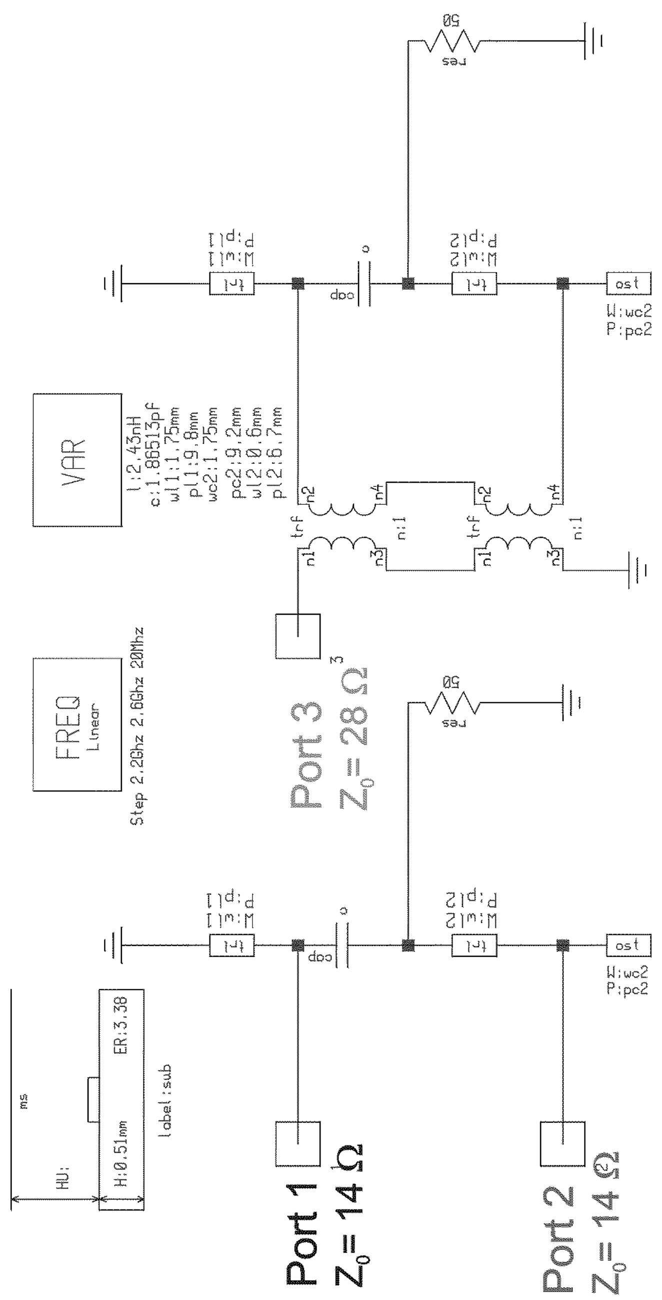


Fig 8 : Circuit diagram from Ansoft Seranade with substituted elements.

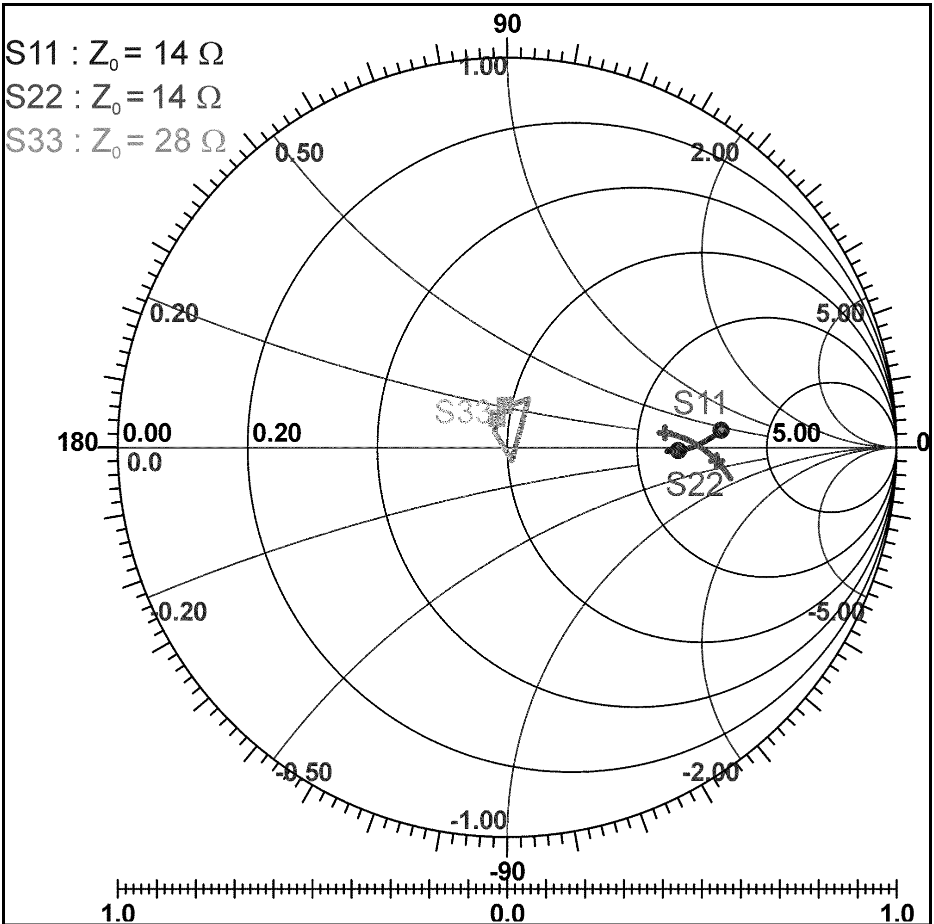
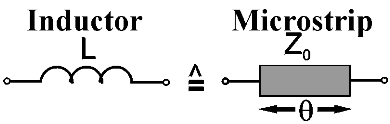


Fig. 9: Simulation result following substitution.

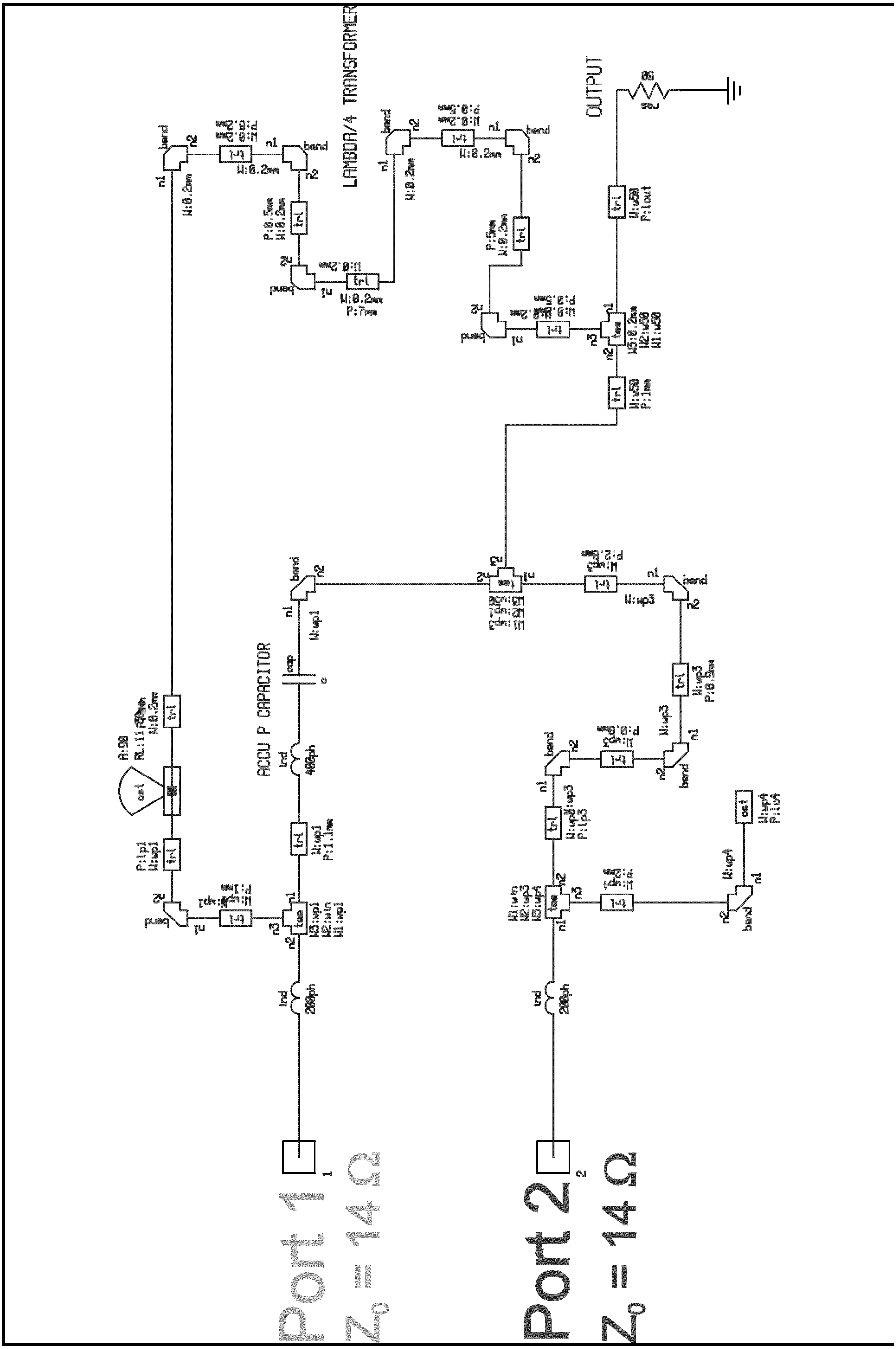
operating bandwidth of the balun, this capacitance is retained as a separate structural element. In the course of the simulation, it will become clear that the feed inductances (tracks) lead to a reduction in the capacitance initially calculated. The reason for this lies in the phase displacement by the connection lines and inductances (e.g. caused by bond inductances in chip capacitors, but also by the inductive element of the capacitor itself).

Substitution of L2 [1]:



$$\omega_{L2} = Z_0 \cdot \sin\theta \qquad \theta < 90^o \left(90^o = \frac{\lambda_{op}}{4} \right)$$

The inductance obtained from the LC balun corresponds to that from L_1. Since for this application the stripline length is limited by the layout, we must select a


LAMBDA/4 TRANSFORMER
OUTPUT
ACCU P CAPACITOR
Port 1
$Z_0 = 14\ \Omega$
Port 2
$Z_0 = 14\ \Omega$

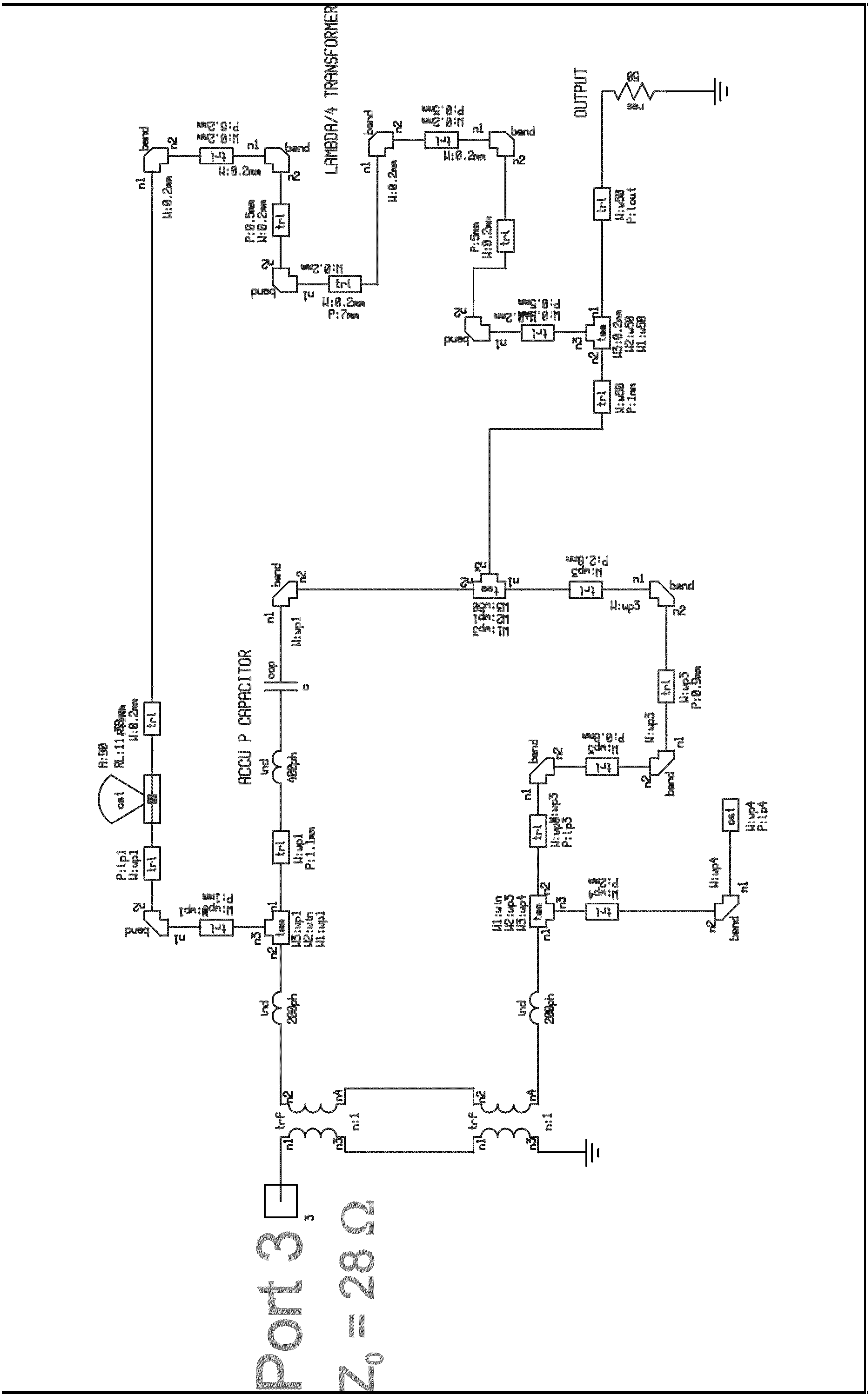


Fig 10 : Overall circuit diagram of balun.

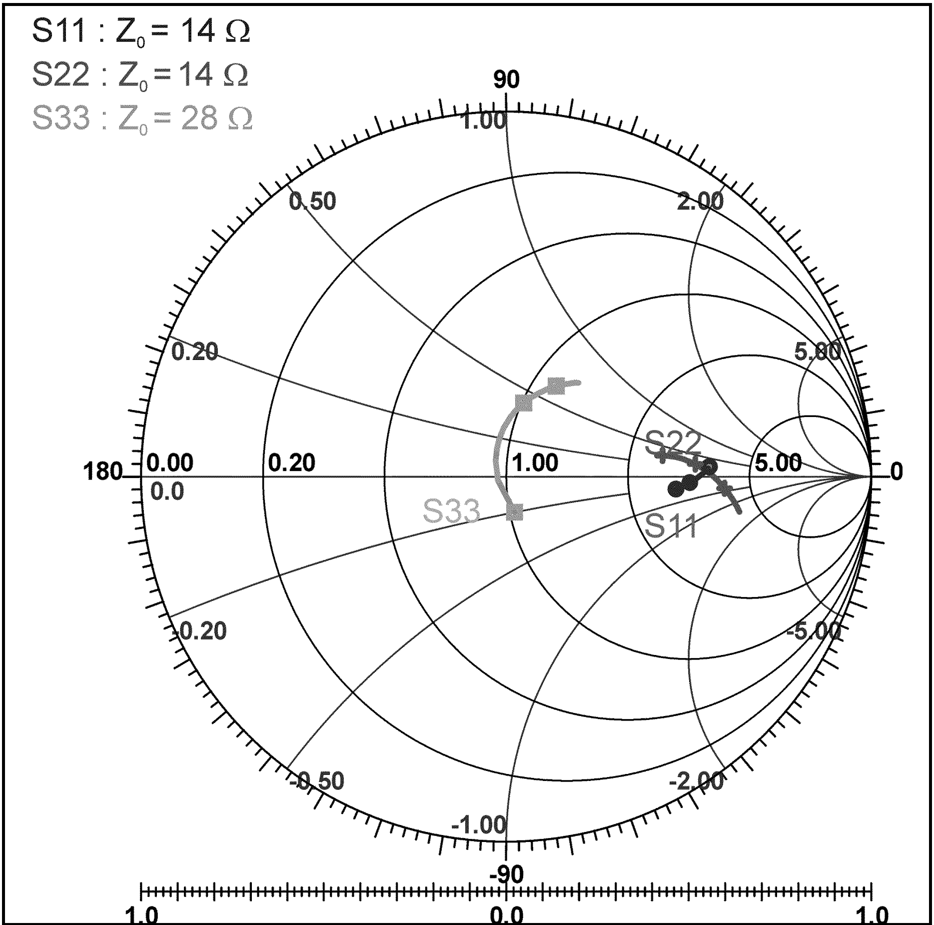


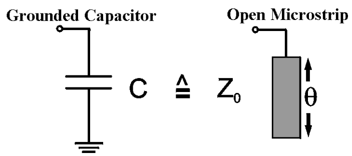
Fig 10 : Balun simulation results.

higher value for Z_0 here, which is expressed in terms of a thinner stripline. If, for example, an impedance is selected of $Z_0 = 72\Omega$ (corresponds here to a width of 0.6mm.), then using the above expression we obtain:

$$\sin\theta = \frac{2\pi \cdot 2.45GHz \cdot 2.43nH}{72\Omega} \approx 0.5$$

and using arcsin (0.5) = 30°, this gives us a microstrip length of approximately 5.6mm.

Substitution of C2 [1]:



$$\omega C_2 = \frac{\tan\theta}{Z_0} \qquad \theta < 90^o \left(90^o \frac{\lambda_{op}}{4} \right)$$

The substitution of the capacitance, C_2, can be very simply accomplished by using an open microstrip. If, as in L_1, we

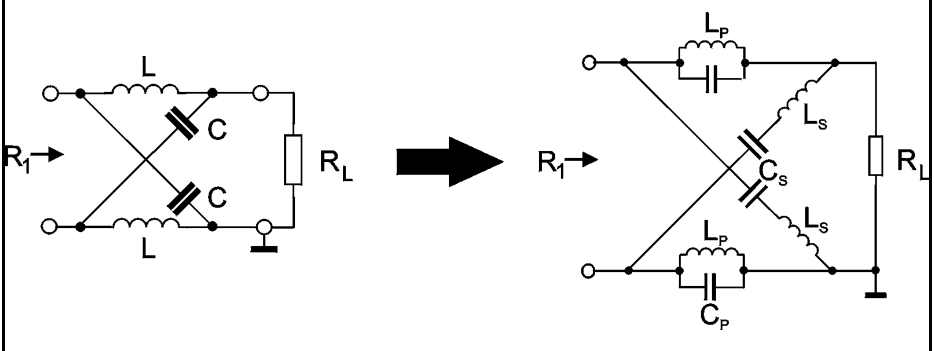


Fig 12 : LC balun bridge with common impedances.

select an impedance, Z_0 = 38Ω, then we obtain

$$\tan\theta = 2\pi \cdot 2.45GHz \cdot 1.73pF \cdot 38\Omega \approx 1$$

and this gives a length of 8.3mm. as the start parameter.

4.3. Optimising of substituted elements

Since the calculated values due to the use of $\varepsilon_{r,eff} = \varepsilon_r$ represent only start parameters ($\varepsilon_{r,eff}$ is actually dependent on both the track width and the frequency), the LC balun must be further optimised. However, this step need not be carried out so intensively, since some further displacement can be brought about through the use of the T-pieces. Ansoft Serenade can calculate a Smith chart which is identical to that of the LC balun (Figs. 8 and 9).

4.4. Insertion of T-pieces and matching of layout to geometrical requirements

We should proceed by stages here, and incorporate and simulate one T-piece after another into the circuit diagram. The incorporation of such T-pieces has a very strong influence on the behaviour of the bridge (alteration of microstrip lengths) and because of the large number of variables it becomes even more difficult to optimise the situation. Fig. 10 shows the resulting overall circuit diagram, with a DC feed for the high-level stage transistors of the power amplifier. Fig. 11 shows the final results of the matching circuit.

4.5. The dual-band LC balun [9]

It would often be an advantage if the Balun could be used for any two different frequency ranges simultaneously (e.g. for 2m and 70cm band applications). This is in fact possible if a parallel resonant circuit is used instead of the inductance, L, and a series resonant circuit instead of the capacitance, C (Fig. 12).

The bridge now exhibits interesting frequency dependent behaviour, as can be seen from Fig. 13.

For frequencies which are lower than the frequency of resonance of the resonant circuit, this balun behaves like a standard LC balun. If the frequency is increased, then the roles of the capacitance and the inductance are reversed. If the bridge is re-designed to become a push-pull power amplifier for the application, then we obtain the circuit diagram shown in Fig. 14. This already contains the power supply feed. For frequencies exceeding 2GHz, the use of radial stubs is recommended, in addition to capacitors with high nominal values.

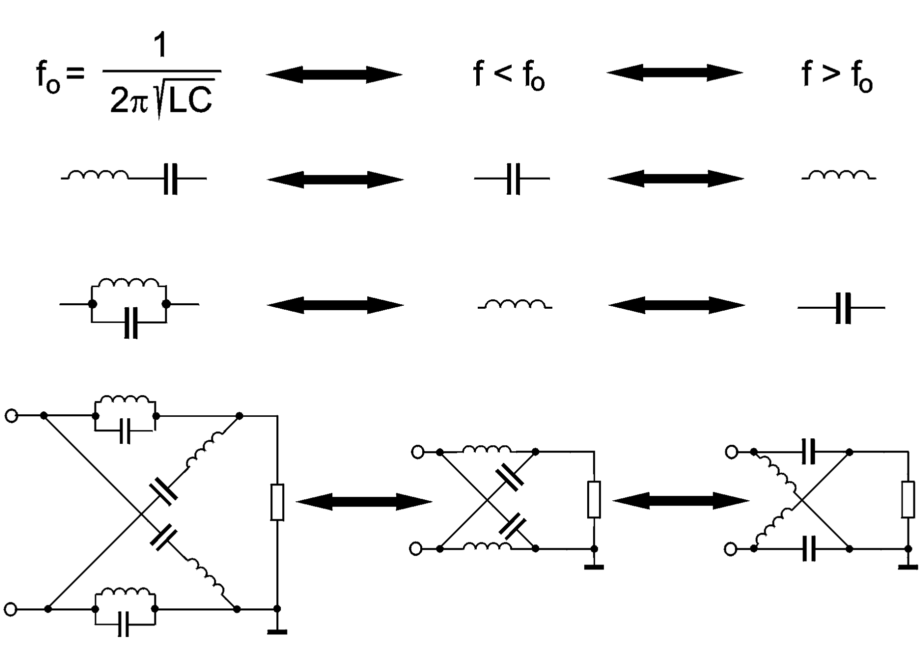


Fig 13 : Behaviour of LC balun with frequency.

For the calculations of the dual-band balun, the following procedures can be specified:

1. First all impedances and the operating frequencies are established. The circuit frequencies are calculated, using the formulae

$$\omega_1 = 2\pi f_1 \quad \text{and} \quad \omega_2 = 2\pi f_2 \quad (\omega_2 > \omega_1)$$

The characteristic impedances of the bridge circuit can be calculated using

$$Z_{C1} = \sqrt{R_1 \cdot R_L} \quad \text{and} \quad Z_{C2} = \sqrt{R_2 \cdot R_L}$$

This makes it clear that even frequency-dependent load impedances can be brought into play for the calculations.

2. For L_s, L_p and C_s, C_p, the following expressions are

$$L_S = \frac{\omega_1 \cdot Z_{C1} + \omega_2 \cdot Z_{C2}}{\omega_2^{\,2} - \omega_1^{\,2}}$$

$$L_p = \frac{Z_{C1} \cdot Z_{C2} \cdot \left(\frac{\omega_2}{\omega_1} - \frac{\omega_1}{\omega_2} \right)}{\omega_1 \cdot Z_{C1} \cdot \omega_2 \cdot Z_{C2}}$$

$$C_S = \frac{\frac{\omega_2}{\omega_1} - \frac{\omega_1}{\omega_2}}{\omega_1 \cdot Z_{C2} \cdot \omega_2 \cdot Z_{C1}}$$

$$C_p = \frac{\omega_1 \cdot Z_{C2} \cdot \omega_2 \cdot Z_{C1}}{Z_{C1} \cdot Z_{C2} \cdot \left(\omega_2^{\,2} - \omega_1^{\,2} \right)}$$

It is again very important to note that these expressions are valid only for ideal structural elements. i.e., for a real layout both the feed sections and the parasitic elements of the structural components have to be taken into account. In real structures, this will mean the resonant circuits have to be “stretched” in their frequencies of resonance.

Thus the use of S-parameter files is just

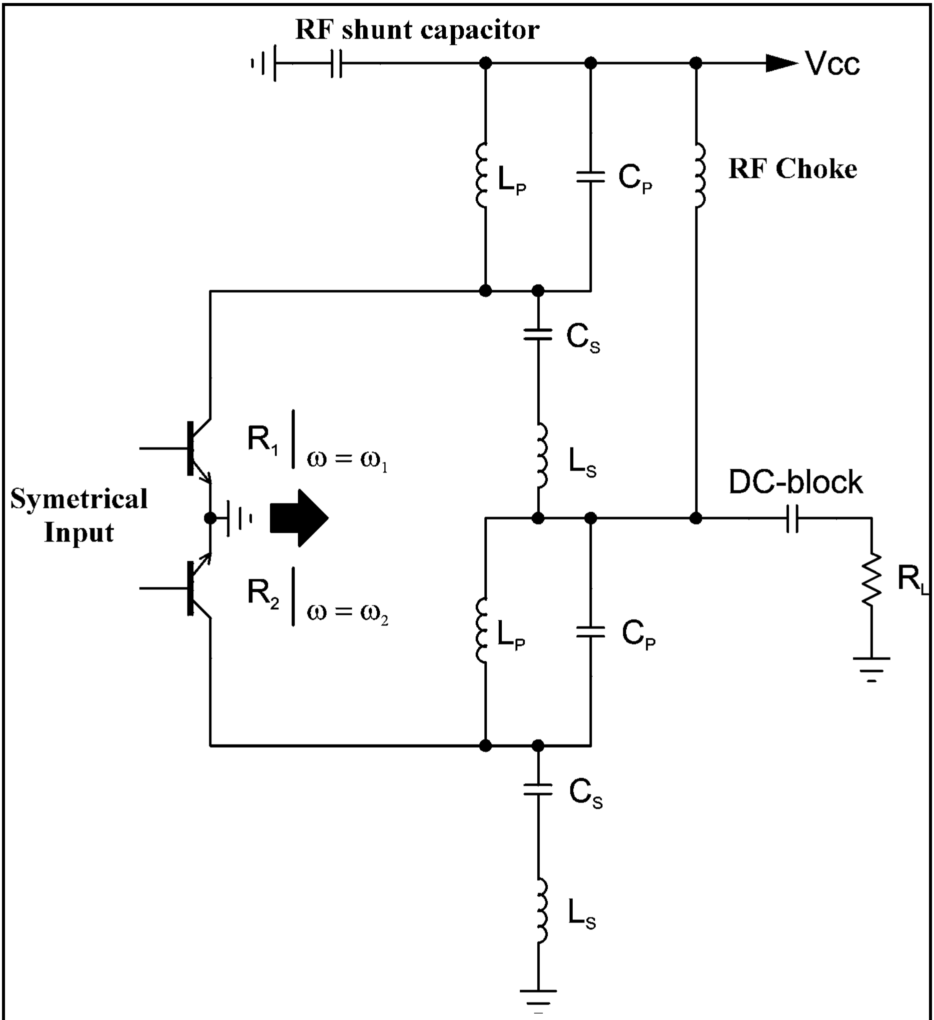


Fig 14 : Dual band LC balun.

as important in the simulation as the precise entering of the layout into the corresponding simulator. Stage by stage insertion of line sections and T-pieces is recommended, as is already done with LC-baluns based on microstrips.

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6.

Software On The Internet:

[S1] Ansoft Serenade 8.5: A restricted student version is available http://www.ansoft.com

[S2] Appcad 2.0: This is a freely available tool for all possible calculaitons involving electrical engineering and metrology http://www.agilent.com/

[S3] Eagleware Genesys: Not to be confused with the Eagle CAD program from Cadsoft. You can also, from time to time, find a demo version of the Eagleware Genesys Suite on this page http://www.eagleware.com